Cosmology

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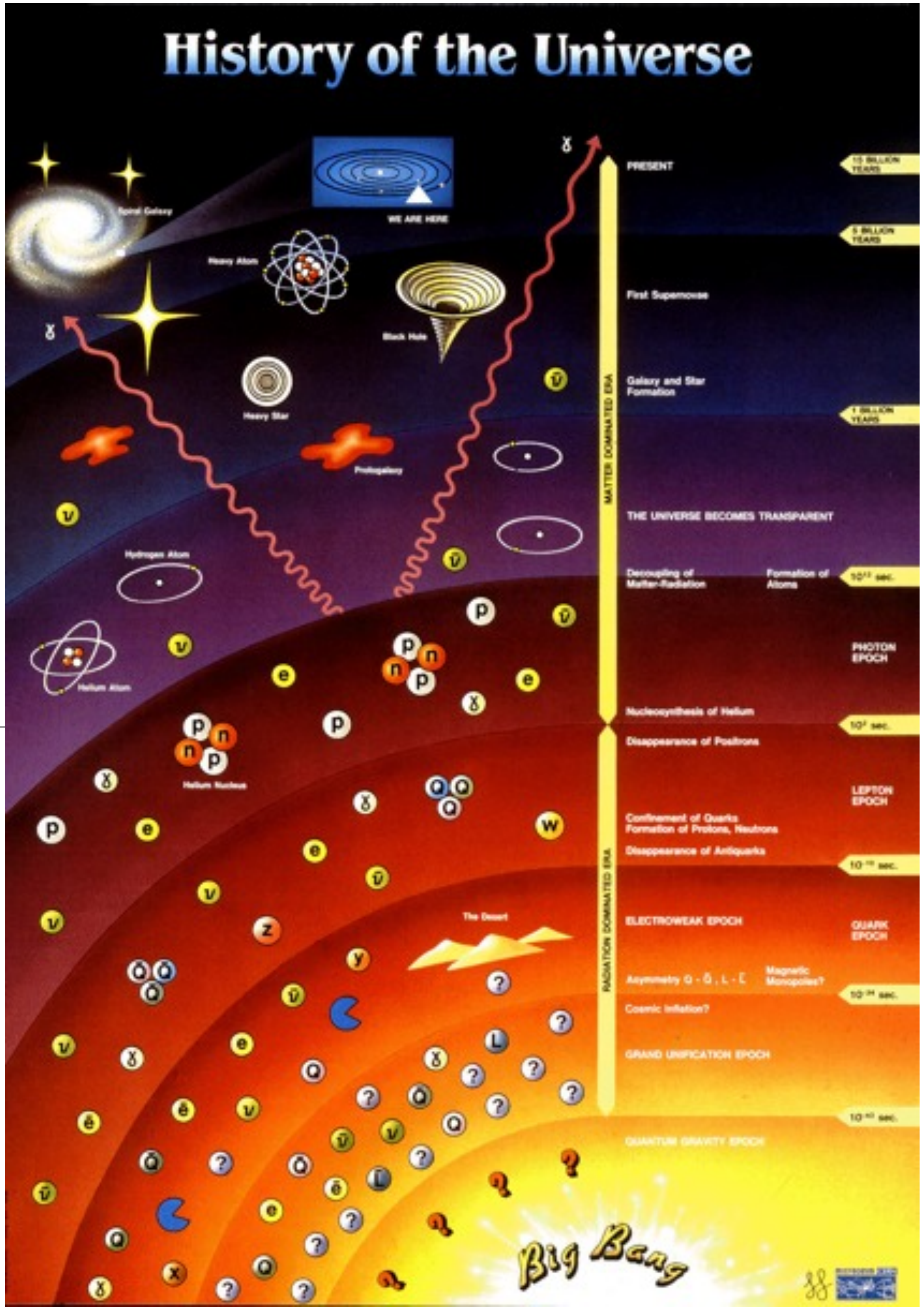


Overview

- Cosmology 1: The homogeneous universe
  - ★The expansion stages of the universe
- Cosmology 2: The inhomogeneous universe
  - ★The cosmic microwave background
  - ★Large scale structure
- Cosmology 3:
  - ★Dark matter
  - ★Dark energy

Cosmology 3

Cosmology 3

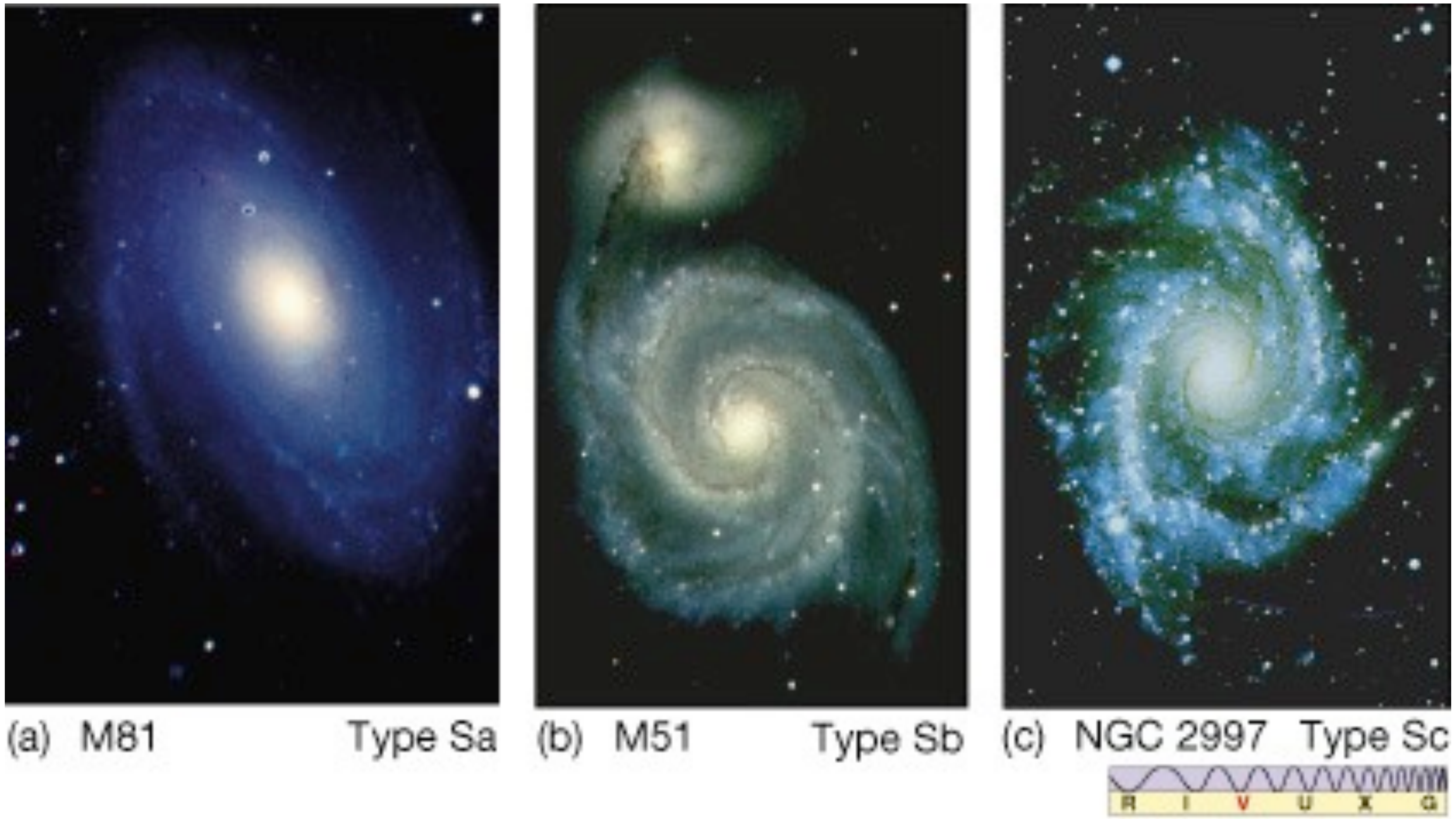
- **Dark matter**

- Evidence for dark matter

- Nature of dark matter ?

Cosmology 3

- Spiral galaxies



(a) M81 Type Sa (b) M51 Type Sb (c) NGC 2997 Type Sc

W. Keel; NOAO; D. Malin/AAT)

Cosmology 3

- **Rotation curves of spiral galaxies**

- spiral galaxies rotate

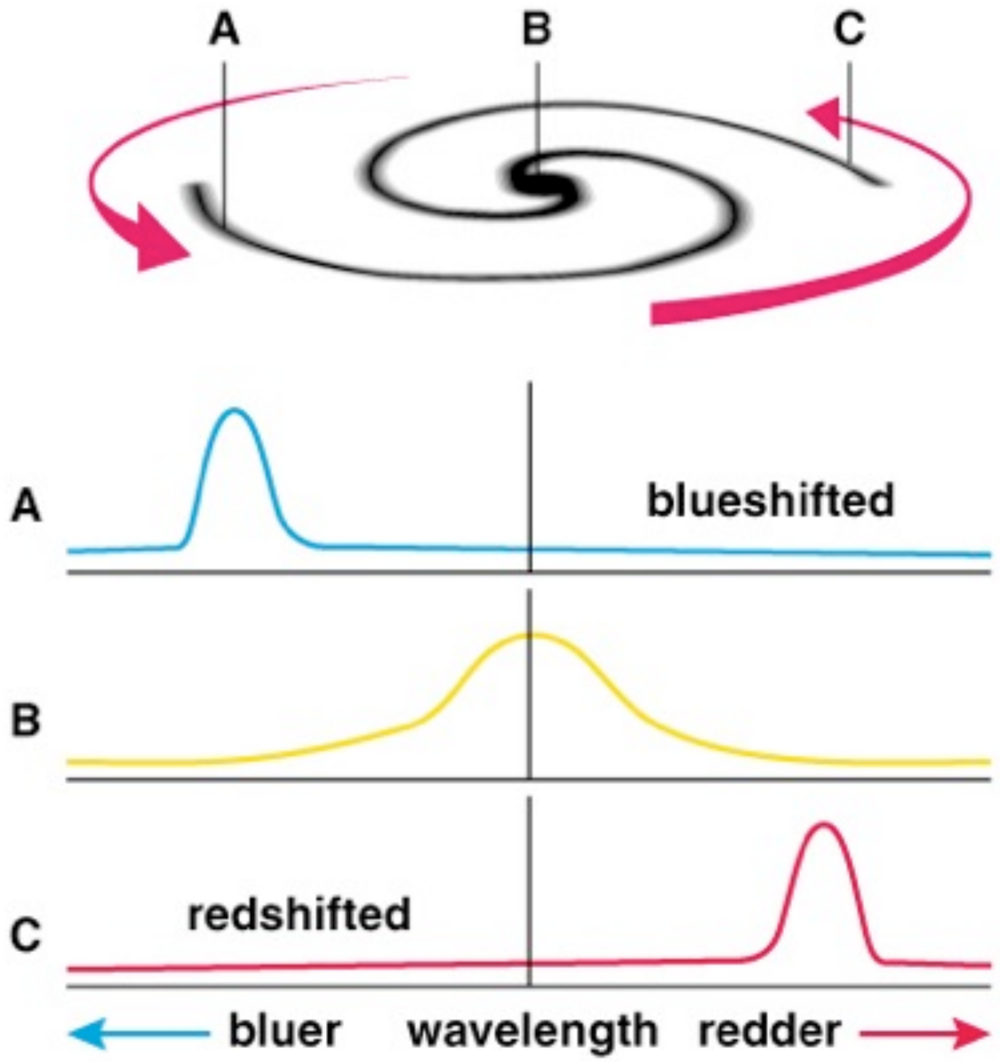
- the mass of a (spiral) galaxy can be estimated from its rotation curve.

- measure rotation velocity around center of the galaxy at a distance r:

$$v_{rot}(r)$$

- use stars or gas clouds (hydrogen)

- observe spectrum, use Doppler shift



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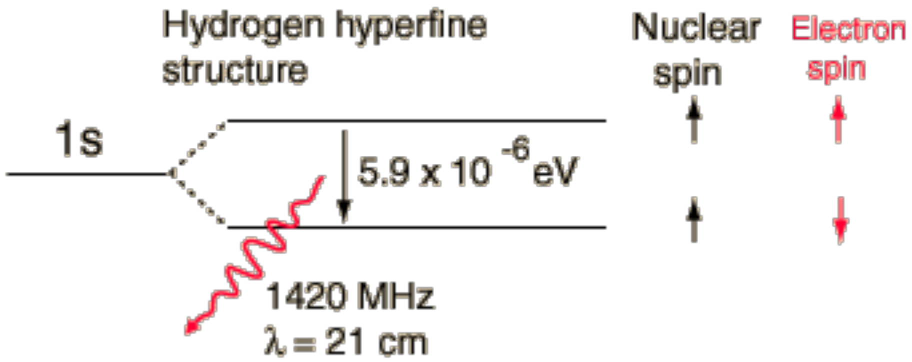
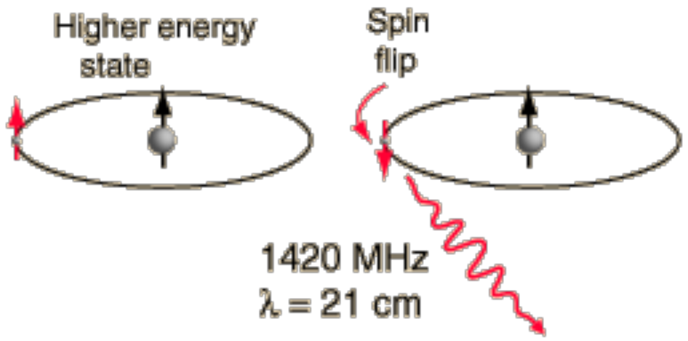
Cosmology 3

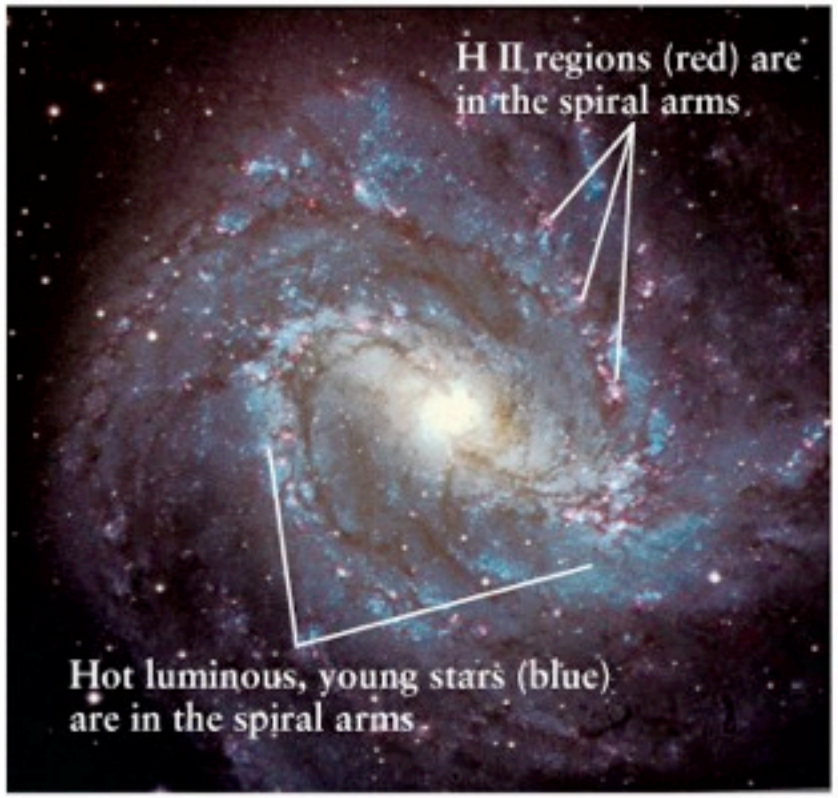
- 21 cm line



observe hydrogen
clouds
by 21 cm line
emission

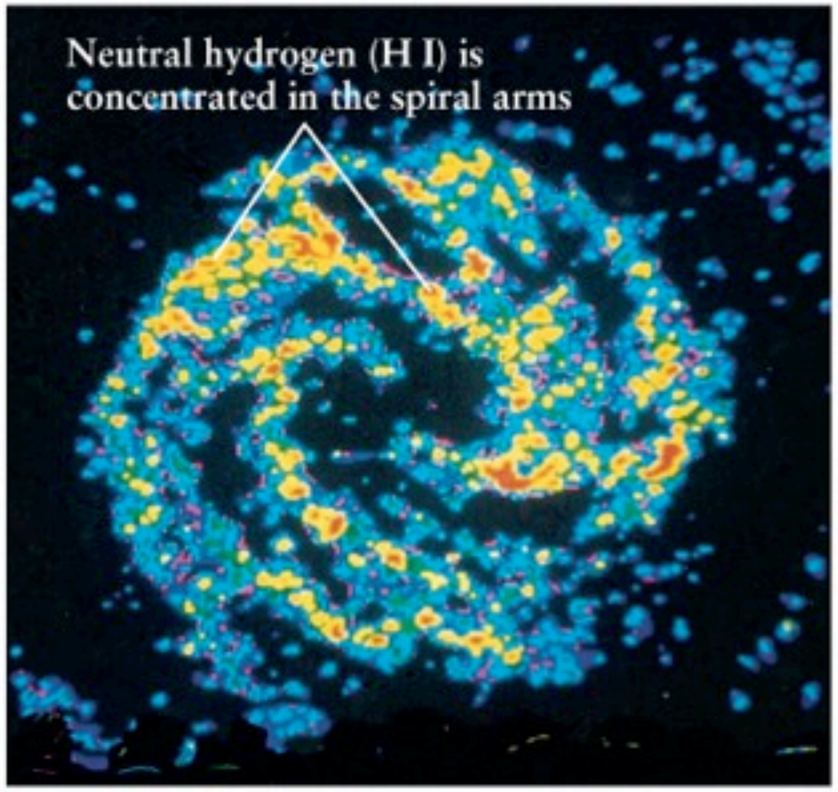


Cosmology 3

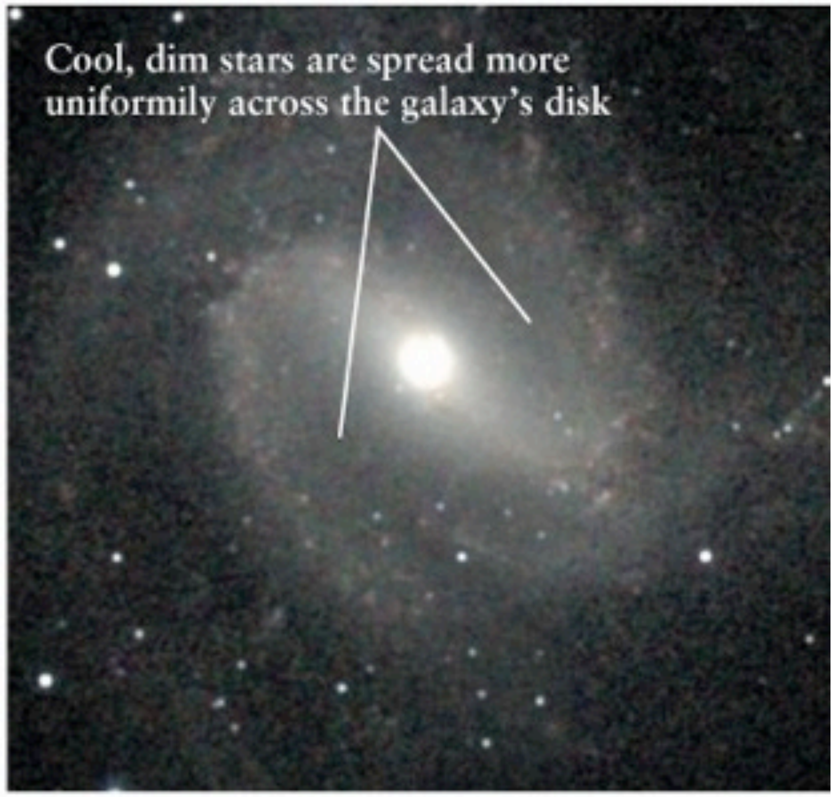

H II regions (red) are in the spiral arms

Hot luminous, young stars (blue) are in the spiral arms

(a) Visible-light view of M83


Neutral hydrogen (H I) is concentrated in the spiral arms

(b) 21-cm radio view of M83


Cool, dim stars are spread more uniformily across the galaxy's disk

(c) Near-infrared view of M83

Cosmology 3

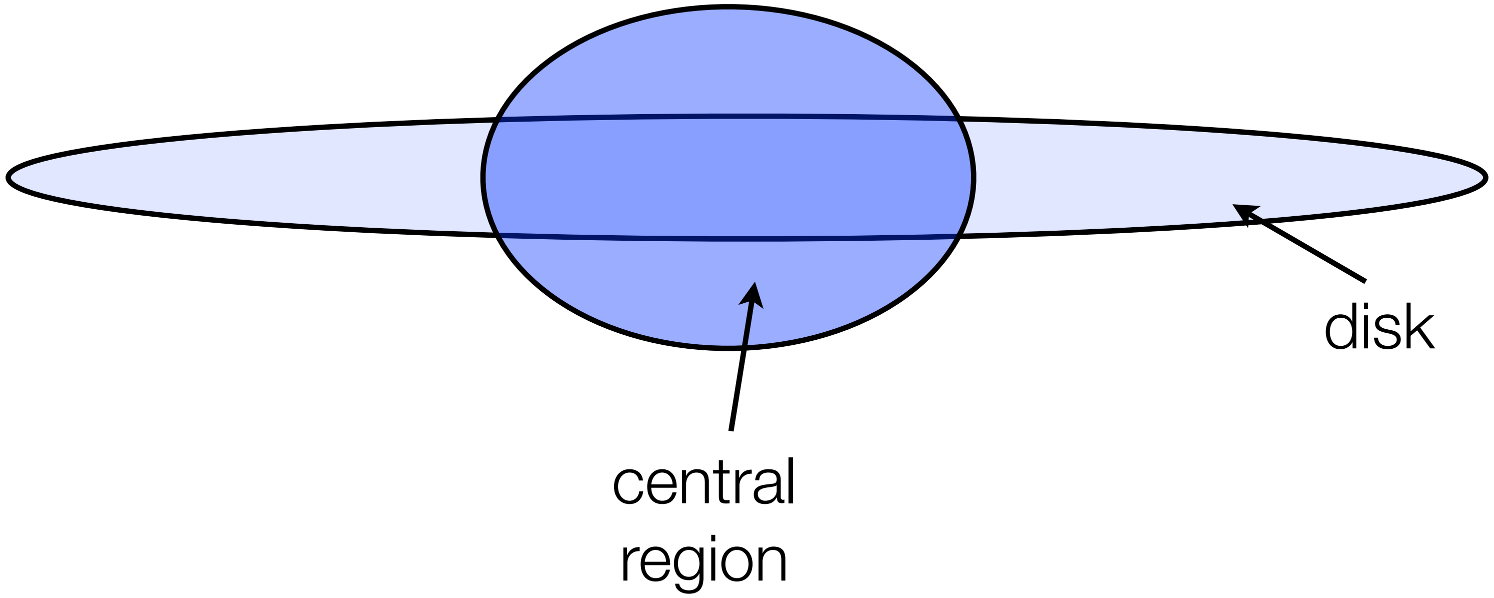
- Assume mass distribution within the central part of galaxy has spherical symmetry: mass inside radius r: $M(\leq r)$

$$\Rightarrow \frac{GM(\leq r)}{r^2} = \frac{v_{rot}^2(r)}{r} \Rightarrow M(\leq r) = \frac{v_{rot}^2(r)r}{G}$$

acceleration due to gravity

centrifugal acceleration

Cosmology 3



- For a star ***in the central region*** one expects (density ~ constant)

$$M_r \propto r^3$$

$$\Rightarrow \frac{Gr^3}{r^2} = \frac{v_{rot}^2}{r} \Rightarrow \boxed{v_{rot} \sim r}$$

Cosmology 3

- For a star ***outside*** of the central region: $M_r \sim const.$

$$\Rightarrow \boxed{v_{rot} \sim r^{-\frac{1}{2}}}$$

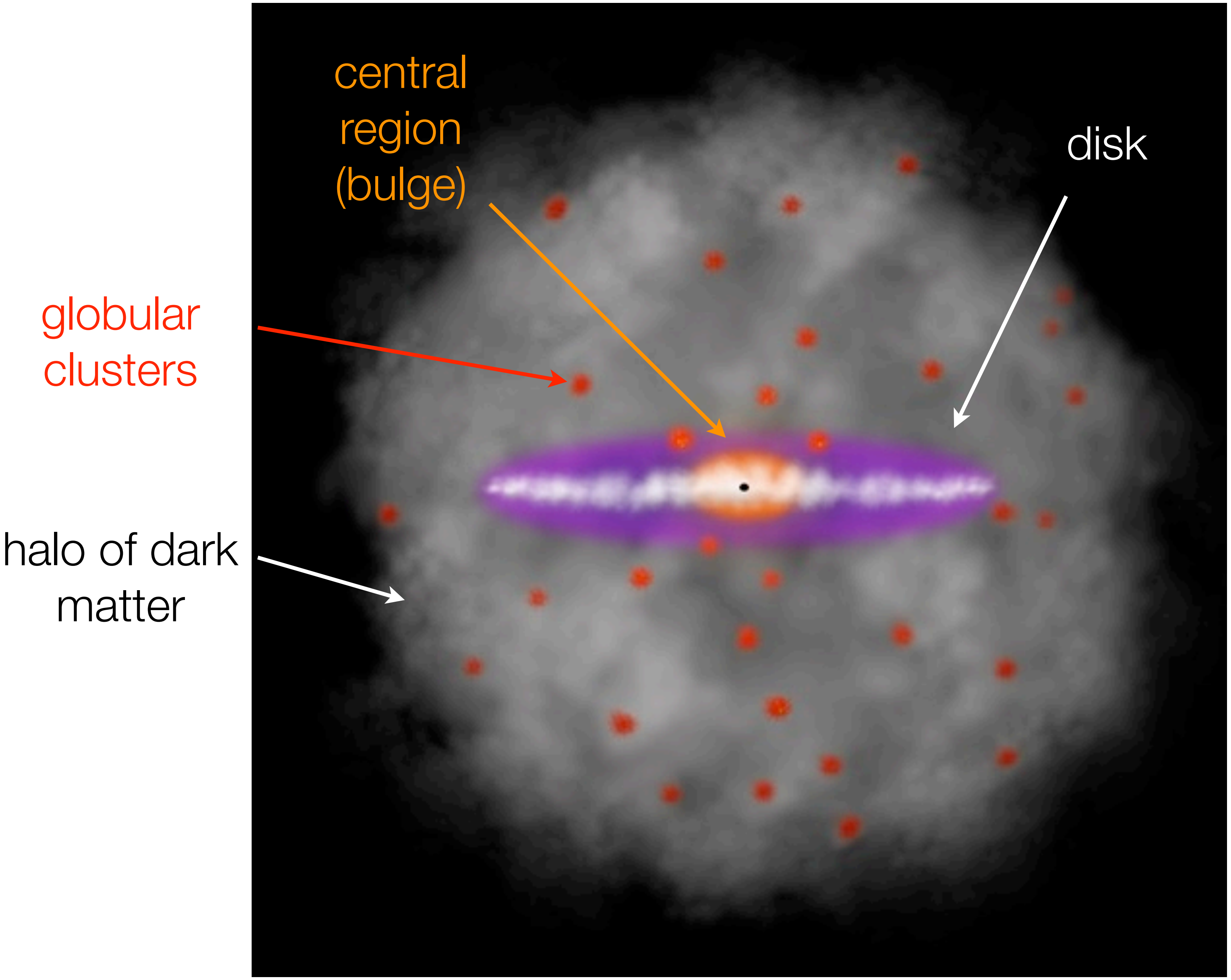
- Therefore the velocity should increase close to the center and decrease at large distance from the galactic center.

- ***But***, what is observed is that the rotation curves are quite flat at large distances of the galactic center.

- This means that the dominant part of the galactic mass, that is ~80%-90%, is in the form of a galactic halo of ***dark matter***.

Cosmology 3

- Milky Way Halo



central region (bulge)

disk

globular clusters

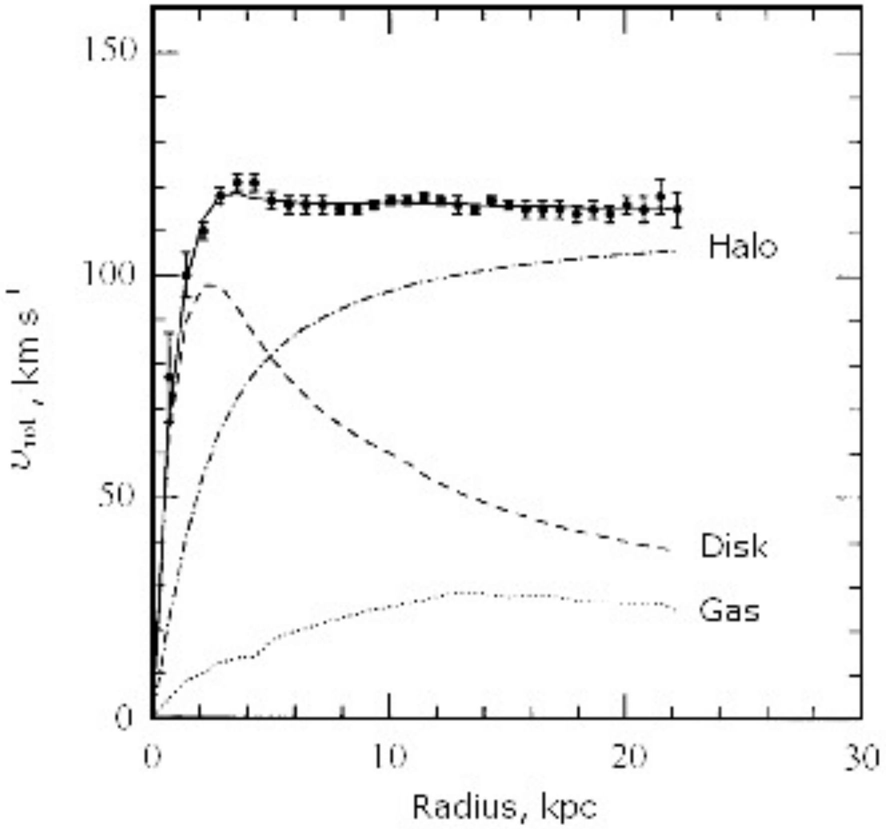
halo of dark matter

Chandra/NASA

Cosmology 3

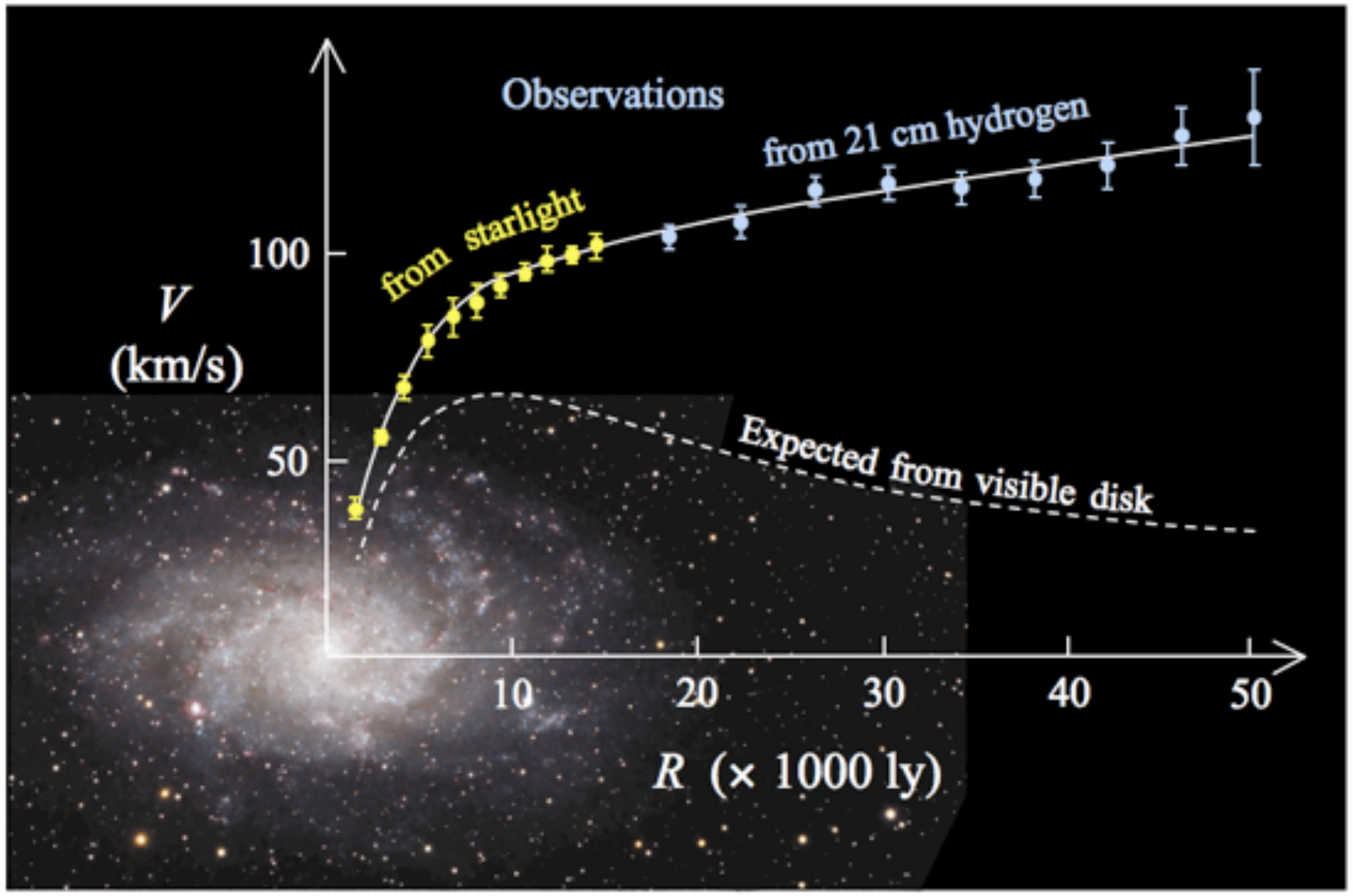
- Rotation curves

- NGC 6503



Doroshkevich et al. 2012

M33



U. Virginia

Cosmology 3

- **Dark matter?**

- Observations show that only a small part of matter in galaxies is luminous (visible) and it makes up only a small part of the total energy density in the universe.

- Primordial nucleosynthesis (BBN-big bang nucleosynthesis) predicts that the baryonic matter density parameter is $\Omega_b \simeq 0.05$

but observations of the luminous part of galaxies lead to a **smaller** value:

$$\Omega_{lum} \simeq 0.01$$

→ a part of dark matter is baryonic

Cosmology 3

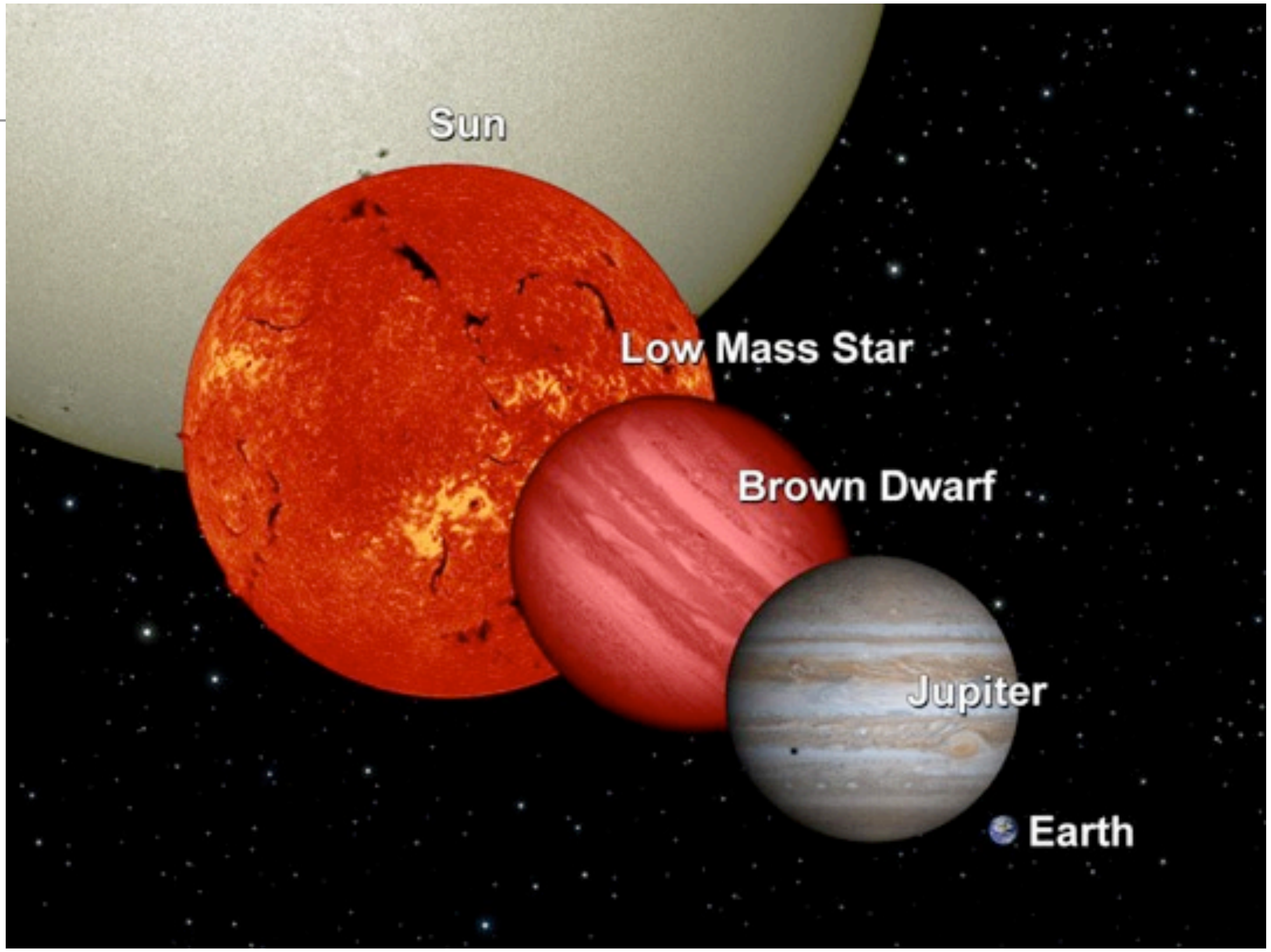
- ***Baryonic dark matter?***

- could be brown dwarfs or Jupiters.....or ***black holes.***

stars with mass less than 10% of the solar mass: their core temperatures are not high enough to start nuclear reaction chain

MACHO=massive astrophysical halo object

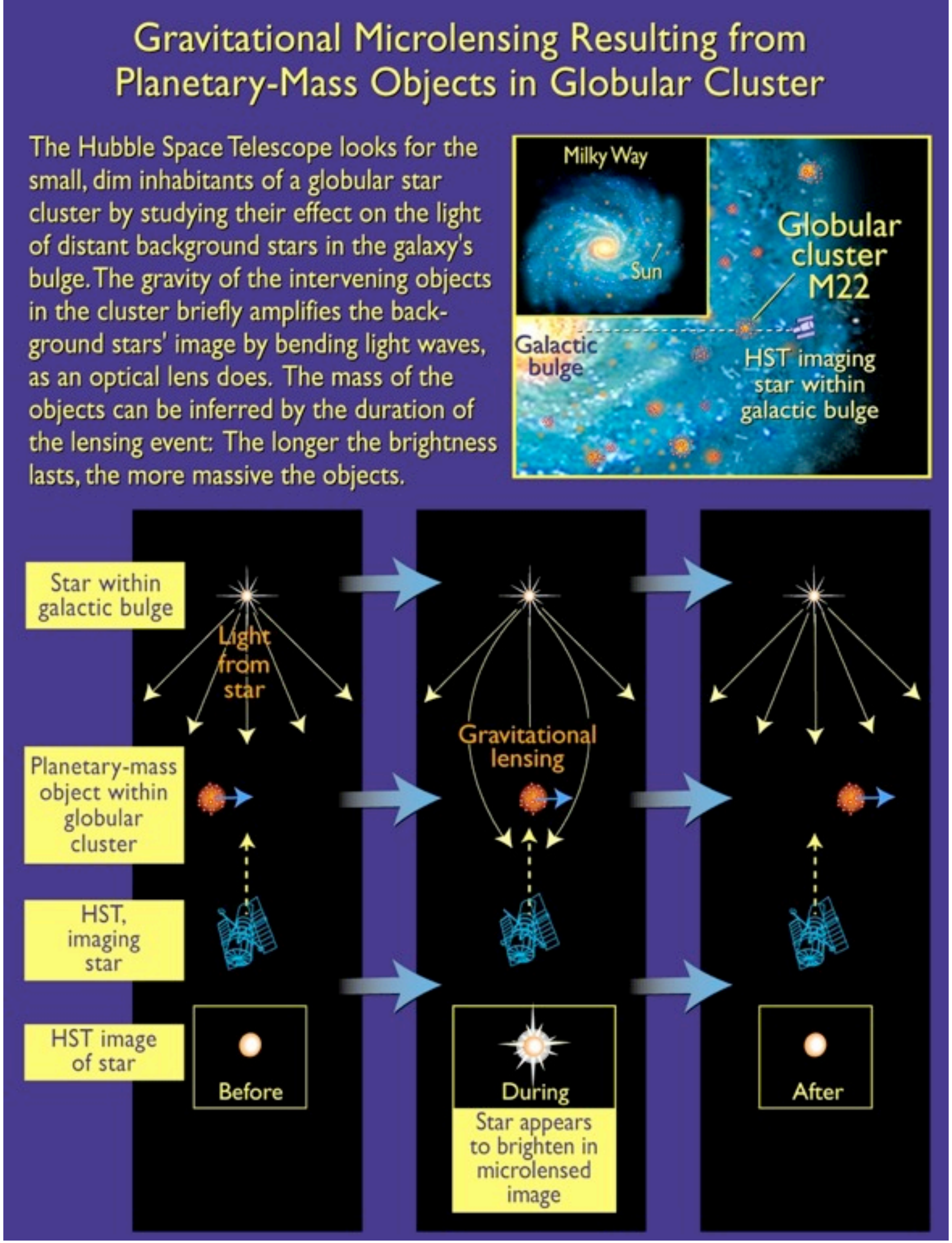
Cosmology 3



NASA

- Observations of MACHOs?

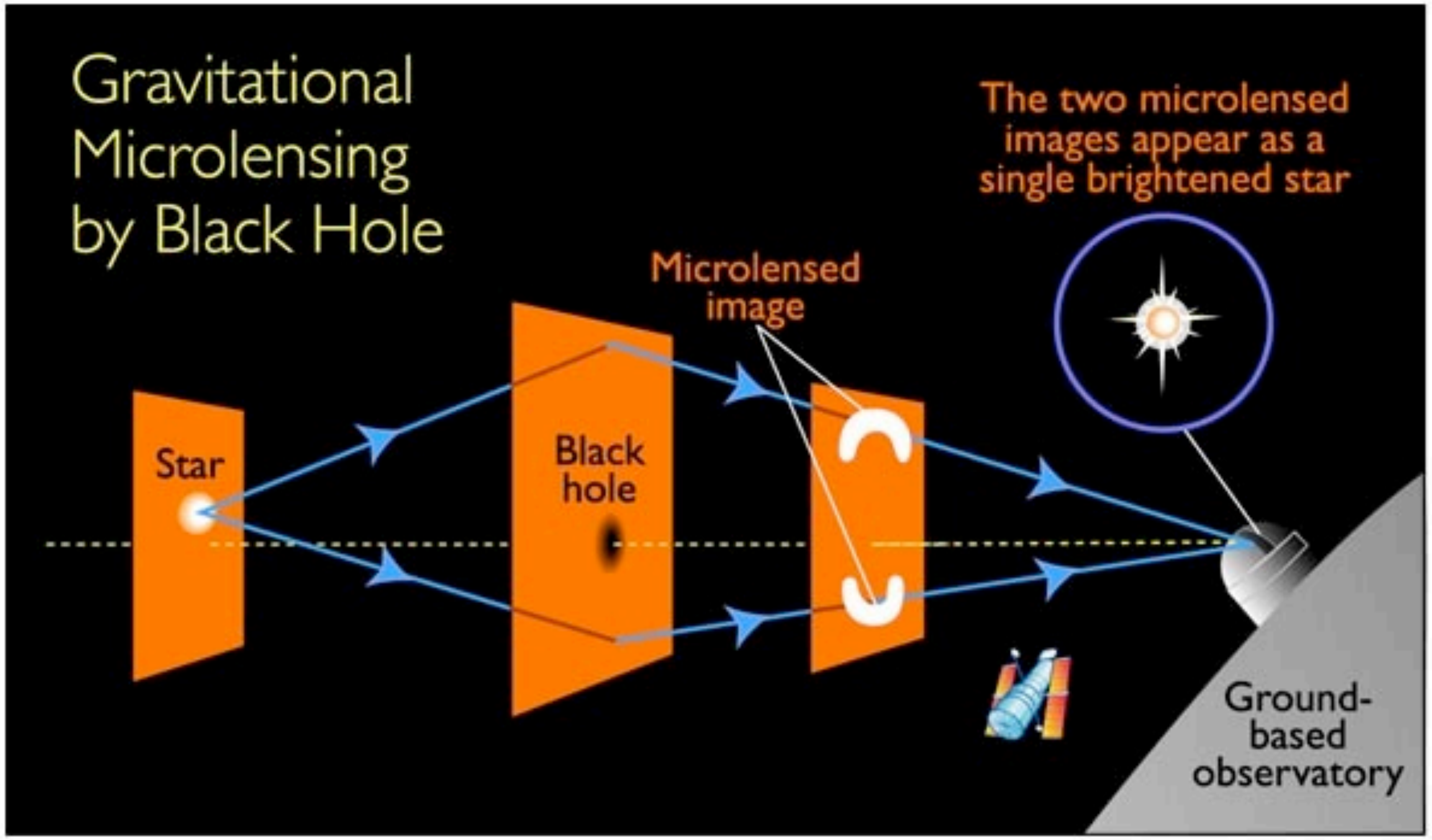
act as gravitational lens → Micro lensing



Gravitational Microlensing Resulting from Planetary-Mass Objects in Globular Cluster

The Hubble Space Telescope looks for the small, dim inhabitants of a globular star cluster by studying their effect on the light of distant background stars in the galaxy's bulge. The gravity of the intervening objects in the cluster briefly amplifies the background stars' image by bending light waves, as an optical lens does. The mass of the objects can be inferred by the duration of the lensing event: The longer the brightness lasts, the more massive the objects.

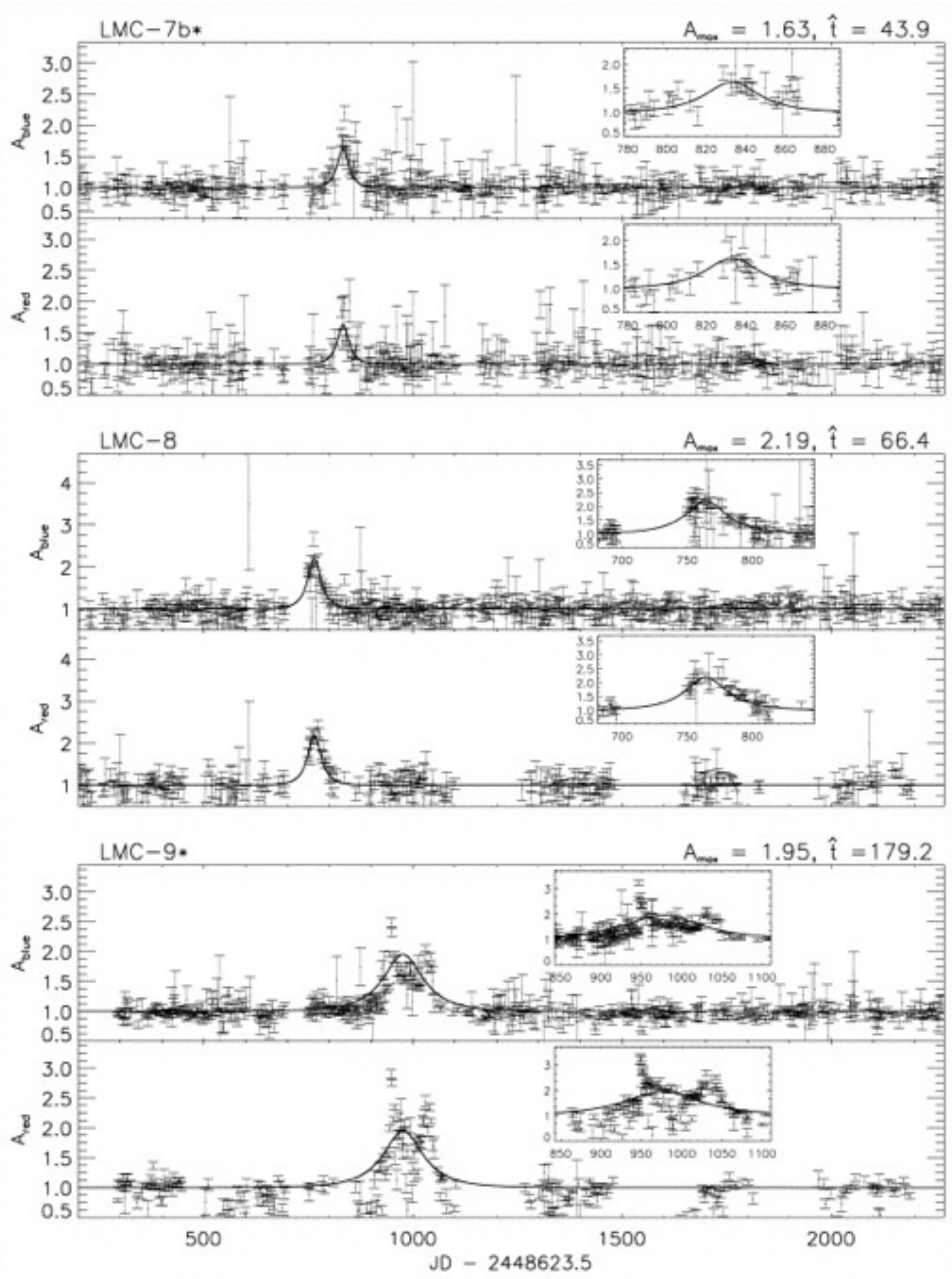
hubblesite.org



The intense gravitational field of a foreground black hole acts like a powerful lens in space. In the diagram, the black hole "lens" distorts and brightens the image of a background star. The gravitational lens smears the star's image into two banana-shaped images with a total surface area several times that of the original stellar disk.

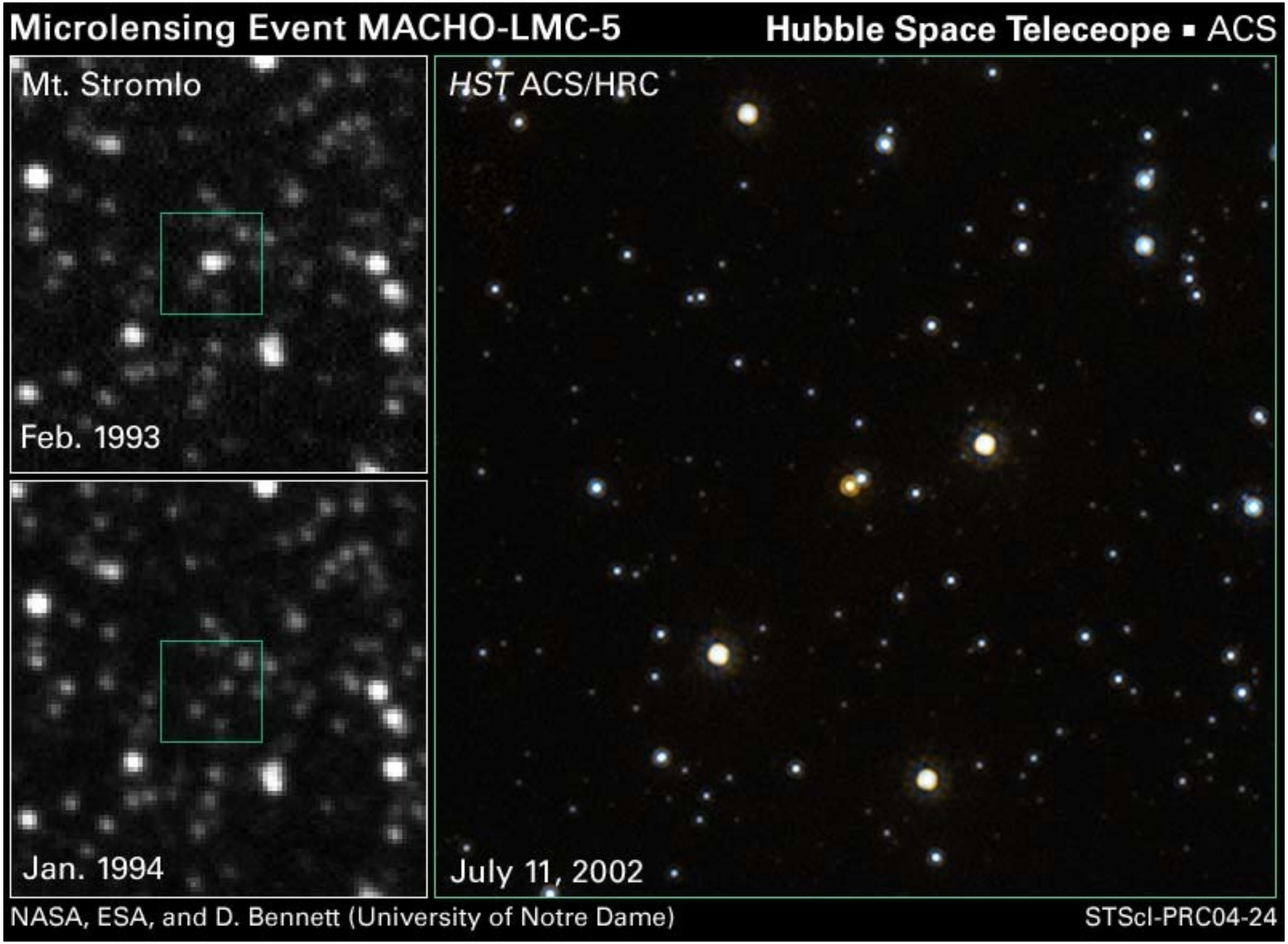
Though the angular separation is shown here, it is 100 times smaller than what HST can resolve. Hence the phenomenon is called "microlensing." HST and other telescopes instead see a brightening of the star as the black hole drifts by, but they do not resolve the multiple images.

hubblesite.org



Light curves
For each object, the top and bottom panels show blue and red passbands, respectively. Flux is in linear units with 1 estimated errors, normalized to the fitted unlensed brightness. Full light curves are shown with 2 day binning; insets of the event regions are unbinned. The thick line shows the fit to unblended microlensing (Table 5), except for probable SN, for which both the unblended fit (solid line) and SN Type Ia fit (dashed line) are shown.

C. Alcock et al. Astrophys. Journal 542 (2000) 281



In the image at top, left, astronomers discovered a subtle brightening of a star [located within the box] due to the effect of gravitational microlensing. This phenomenon occurs when a foreground star, in this case a dim red star, passes in front of a much more distant star and amplifies its light. Astronomers were engaged in a large-scale search for microlensing events in the halo of our Milky Way galaxy. They were looking in the direction of the Large Magellanic Cloud, a satellite galaxy of our Milky Way. The image was taken in February 1993 with the 50-inch telescope at the Mount Stromlo Observatory in Australia. The box represents the field of view of NASA's Hubble Space Telescope.

When astronomers used the Mount Stromlo telescope to observe the same region almost a year later, the background star had returned to its normal brightness. The foreground star — the "natural lens" that had magnified the background star — had moved away. The ground-based telescope's vision, however, was not keen enough to resolve the stars separately.

So, astronomers used the sharp vision of the Hubble telescope to resolve the stars as two separate objects. The foreground star is red, and is in our galaxy's halo. The background star is blue, and is in the Large Magellanic Cloud. The image was taken on July 11, 2002.

Cosmology 3

- More evidence of dark matter....
- the CMB → $\Omega_{CDM} = 0.265$ (Planck13)

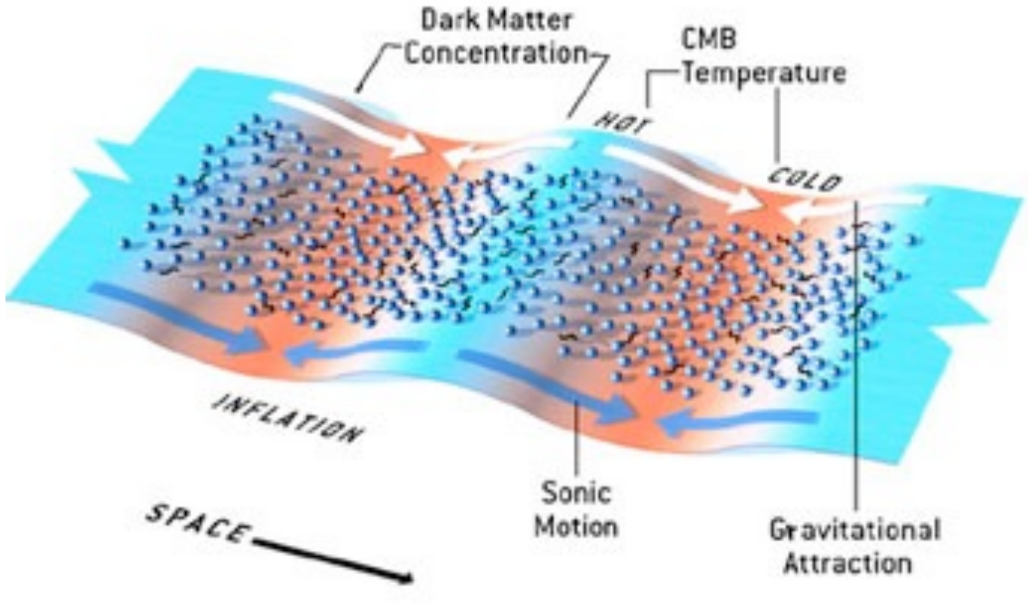
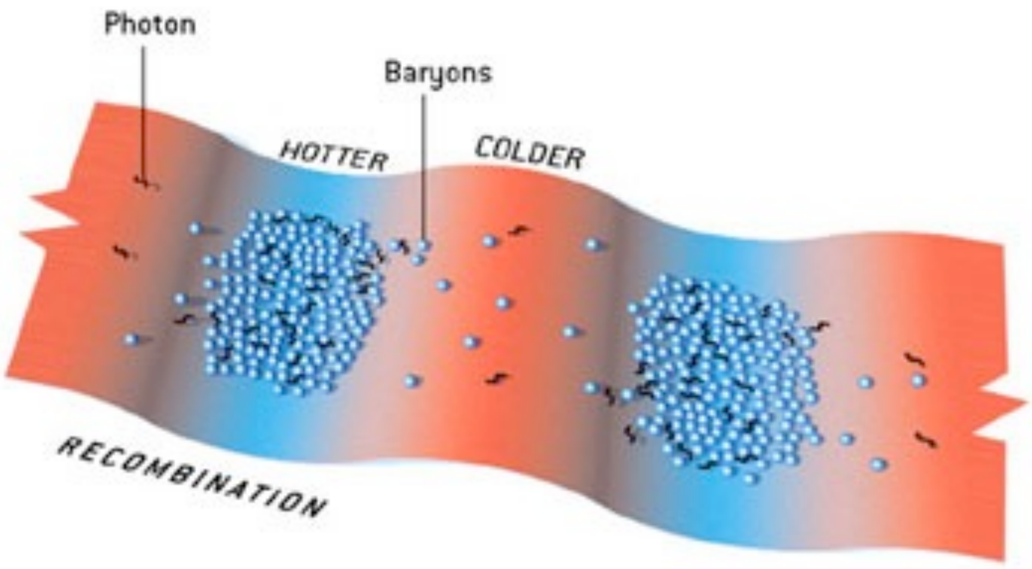


Illustration of the origin of the first acoustic peak in the CMB temperature angular power spectrum



Hu

Cosmology 3

- **Non baryonic dark matter**

- Particles created in the very early universe which are stable so that they are present today

- Candidates:

    - massive neutrinos

    - axions

    - WIMPs=weakly interacting massive particles (example: supersymmetric partners of the standard model particles)

Cosmology 3

- Neutrinos (SM)

- Determine moment of decoupling of neutrinos

- In the early universe neutrinos stay in equilibrium with the rest of the cosmic plasma by

$$\bar{\nu}_e \nu_e \leftrightarrow e^+ e^-$$

$$\nu_e e^- \leftrightarrow \nu_e e^- \qquad \text{etc.}$$

- Cross section of *weak interactions* given by

$$\sigma \simeq G_F^2 T^2$$

- where G_F is the Fermi constant.

$$G_F = 1.166 \times 10^{-5}\ \text{GeV}^{-2}$$

Cosmology 3

- The number density of light particles (relativistic limit) evolves as

$$n \sim T^3$$

➡ interaction rate (per neutrino) is

Recall: Hubble parameter in radiation dominated era evolves as

$$H = 1.66 g_*^{\frac{1}{2}} \frac{T^2}{M_P}$$

$$\Gamma_{int} = n\sigma|v| \simeq G_F^2 T^2 \times T^3$$

$$\boxed{\Gamma_{int} \simeq G_F^2 T^5}$$

$$\frac{\Gamma_{int}}{H} \simeq \frac{G_F^2 T^5}{T^2/M_P} \longrightarrow \boxed{\frac{\Gamma_{int}}{H} \simeq \left(\frac{T}{1\ \mathrm{MeV}}\right)^3}$$

$$M_P = 1.22 \times 10^{19}\ \mathrm{GeV}$$

$$G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Cosmology 3

- ➡ At temperatures above 1 MeV, interaction rate larger than expansion rate
  - ➡ neutrinos coupled to rest of the plasma.
- ➡ At temperatures below 1 MeV the interaction rate falls below the expansion rate and the interactions of the neutrinos with the particles of the cosmic plasma are no longer efficient to keep them in equilibrium:
- ➡At a temperature ~1 MeV light neutrinos decouple from the plasma. Afterwards their temperature evolves as 1/a.

Cosmology 3

- At the time of neutrino decoupling, photons, neutrinos and the rest of matter (which was in thermal equilibrium) had the same temperature.

- If the photon temperature would evolve as a^{-1} , neutrinos and photons would have the same temperature at present.

- But, photon and neutrino are at different temperatures today because g_* changes.

relativistic degrees of freedom (depends on temperature)

- The change in g_* occurs when the temperature falls below $T \simeq m_e \sim 0.5 \text{ MeV}$ (correpsonds to $5 \times 10^9 \text{ K}$). Below this temperature photons are not energetic enough to create e^+e^- pairs.

Cosmology 3

$$\begin{tikzcd}
 & e^+e^- \leftrightarrow \gamma\gamma \arrow[dl, "\text{suppressed}"'] \arrow[dr] & \\
\xcancel{e^+e^- \leftarrow \gamma\gamma} & & e^+e^- \rightarrow \gamma\gamma \arrow[d] \\
 & & e^+e^- \text{ pairs disappear}
\end{tikzcd}$$

➡ Change in g_* :

Cosmology 3

- At temperatures $T_D > T \gtrsim m_e$ neutrinos are decoupled, their entropy is conserved.

temperature at neutrino decoupling

Photons are in equilibrium with electrons and positrons:

$$g_*(\gamma, e^+, e^-) = 2 + \frac{7}{8} \times 4 = \frac{11}{2}$$

Cosmology 3

- At temperatures $T \ll m_e$: $g_*(\gamma) = 2$
- Conservation of entropy $S = g_*(Ta)^3 = const.$

$$g_{*,before}(Ta)^3_{before} = g_{*,after}(Ta)^3_{after}$$

before

after

annihilation of e^+e^- pairs

$$\Rightarrow \quad \frac{(Ta)^3_{after}}{(Ta)^3_{before}} = \frac{g_{*,before}}{g_{*,after}} = \frac{\frac{11}{2}}{2} = \frac{11}{4}$$

$$\boxed{T = T_\gamma}$$

Cosmology 3

- The temperature of the (decoupled) *neutrinos* follows exactly

$$T_\nu = \frac{K}{a}$$

K. constant

$$\Longrightarrow \qquad (aT_\nu)_{before} = (aT_\nu)_{after} = K$$

- Before decoupling neutrinos had the same temperature as the photons, upto the moment of decoupling. For temperatures

$$T_D > T \gtrsim m_e$$

$$\Longrightarrow \qquad T_\gamma = T_\nu$$

$$T_{\gamma,before} = T_{\nu,before}$$

Cosmology 3

- Therefore

$$(aT_\gamma)_{after} = \left(\frac{11}{4}\right)^{\frac{1}{3}} (T_\gamma a)_{before}$$
$$= \left(\frac{11}{4}\right)^{\frac{1}{3}} (T_\nu a)_{before}$$

- with $(T_\nu a)_{before} = (T_\nu a)_{after}$

⇒ $$(aT_\gamma)_{after} = \left(\frac{11}{4}\right)^{\frac{1}{3}} (T_\nu a)_{after}$$

$$\boxed{\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{\frac{1}{3}} \simeq 1.4}$$

after annihilation of e^+e^- pairs until the present

Cosmology 3

- Therefore at present there is a background of (light) neutrinos at a temperature

CMB: $T_{\gamma,0} \simeq 2.73\ \mathrm{K}$

$$T_{\nu,0} = \left(\frac{11}{4}\right)^{-\frac{1}{3}} T_{\gamma,0} \Rightarrow T_{\nu,0} \simeq 1.95\ \mathrm{K}$$

but it has not been *directly* detected yet.

- Number density of neutrinos plus antineutrinos today: $n_\nu = \frac{3}{11} n_\gamma = 113\ \mathrm{cm}^{-3}$

- This leads to a bound on the total mass assuming that the neutrino contribution does not overclose the universe, that is $\Omega = \frac{\rho}{\rho_c} \leq 1$

⇒

$$\sum_{e,\mu,\tau} = m_\nu c^2 \leq 47\ \mathrm{eV}$$

Cosmology 3

- Light neutrinos as dark matter have the problem that they were relativistic at decoupling (T~1 MeV) → *hot dark matter*

- They stream freely under gravity and tend to damp out density perturbations.

➡ Fraction of hot dark matter has to be subdominant w.r.t. to cold dark matter.

- **Constraints on number of neutrino species: BBN and CMB**

- For SM neutrinos:

$$\rho_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{eff}\right)$$

➡ changing N_{eff} changes expansion rate (recall $H^2 \sim \rho$)

Cosmology 3

➡ changes temperature of freeze-out of n ⟷ p and the ratio

$$\frac{n}{p} = e^{-\frac{Q}{T_D}}$$

➡changes primordial Helium fraction

$$Y = \frac{m_{He-4,total}}{m_{bariones,total}}$$

⇨ $$Y = \frac{4\frac{n_n}{2}}{n_n + n_p} = \frac{2\frac{n}{p}}{1 + \frac{n}{p}}$$

➡ $$\boxed{N_{eff}^{BBN} = 3.28 \pm 0.28}$$

PDG 14

Cosmology 3

- CMB

- the change in the expansion rate at decoupling changes the sound horizon :

$$r_s = \int_0^{t_d} c_s \frac{dt}{a} = \int_0^{a_d} \frac{c_s da}{a^2 H}$$

and the damping scale

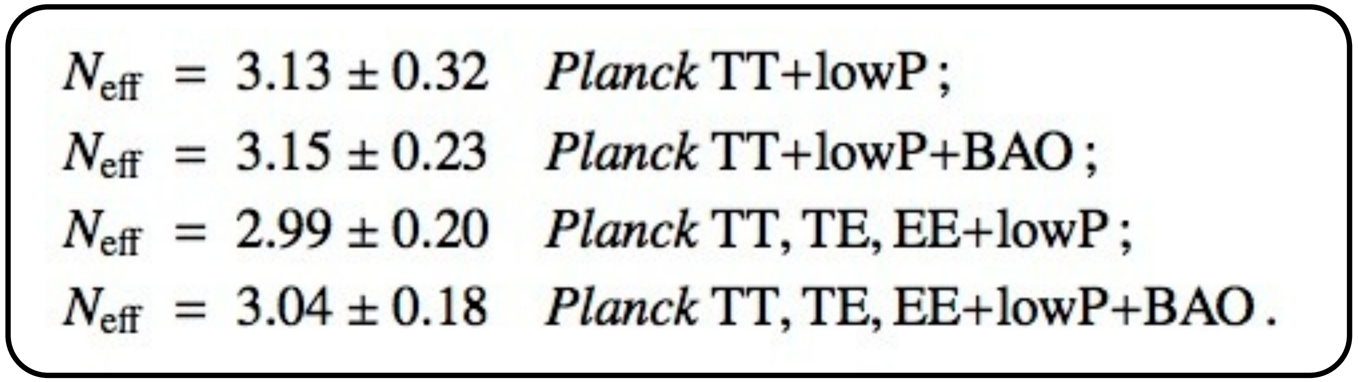
$$k_\gamma^{-2}(z) = \int_z^\infty \frac{dz}{6H(z)(1+R)\dot{\tau}} \left(\frac{16}{15} + \frac{R^2}{1+R} \right) .$$

$$\dot{\tau} = n_e \sigma_T \frac{a}{a_0} \qquad R = \frac{3}{4} \frac{\Omega_{b,0}}{\Omega_{\gamma,0}} (1+z)^{-1}$$

➡ increasing N_{eff} decreases damping scale → increases small scale anisotropies.

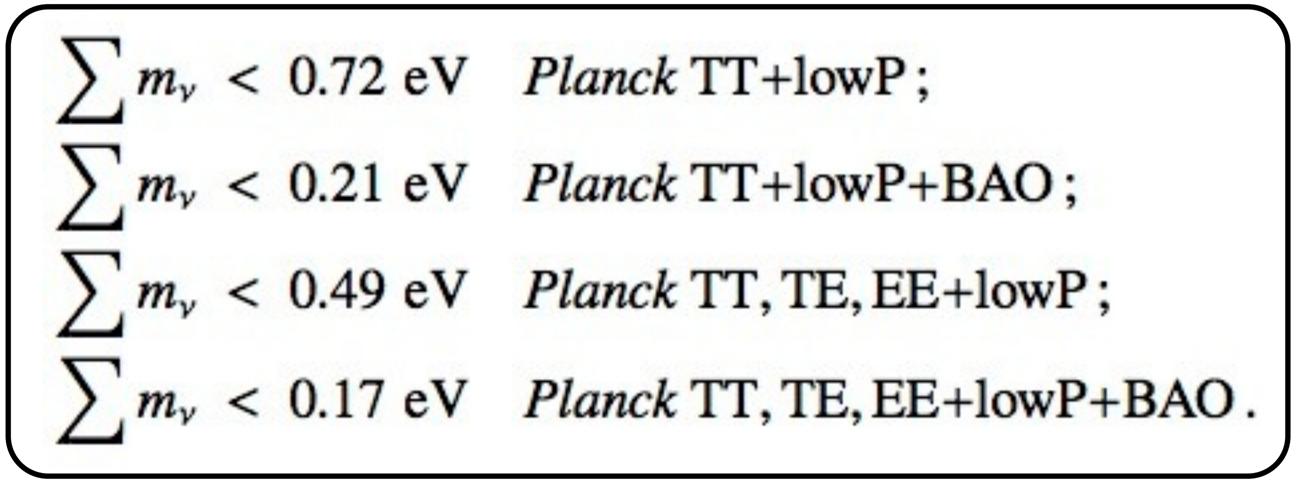
Cosmology 3

Planck 15 68%CL



$$\begin{aligned} N_{\rm eff} &= 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,; \\ N_{\rm eff} &= 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,; \\ N_{\rm eff} &= 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,; \\ N_{\rm eff} &= 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,. \end{aligned}$$

- Assuming a degenerate mass hierarchy for 3 species of massive neutrinos **Planck 15** constrains total mass at 95%CL:



$$\begin{aligned} \sum m_\nu &< 0.72\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,; \\ \sum m_\nu &< 0.21\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,; \\ \sum m_\nu &< 0.49\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,; \\ \sum m_\nu &< 0.17\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,. \end{aligned}$$

Cosmology 3

- So there is indirect evidence of the cosmic neutrino background. What about direct detection of the cosmic neutrino background?
- Experiments using induced beta decay $\nu_e + {}^3H \rightarrow {}^3He + e^-$
- KATRIN
- PTOLEMY

Cosmology 3

- **WIMPs** (=weakly interacting massive particles)

- assumed to be non relativistic at the time of their decoupling of the rest of the cosmic plasma

→ **Cold Dark Matter**

- General constraint on hypothetical WIMP χ

- "Freeze-out" of interactions when annihilation rate $\chi\bar{\chi}$ falls below expansion rate:

$$N\langle\sigma v\rangle \leq H$$

number density

σ. WIMP-antiWIMP annihilation cross section

v. relative velocity of $\chi\bar{\chi}$

Cosmology 3

- Assuming freeze-out during radiation-dominated era

$$N = g\left(\frac{mT}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m-\mu}{T}} \qquad H = 1.66 g_*^{\frac{1}{2}} \frac{T^2}{M_P}$$

- Determine freeze-out temperature T_D from $N(T_D)\langle\sigma v\rangle = H(T_D)$

- Determine number density at present: $N(T_0) = N(T_D)\left(\frac{T_0}{T_D}\right)^3$

- Determine density parameter:

$$\Omega_\chi = \frac{N(T_0)m}{\rho_c} \Rightarrow$$

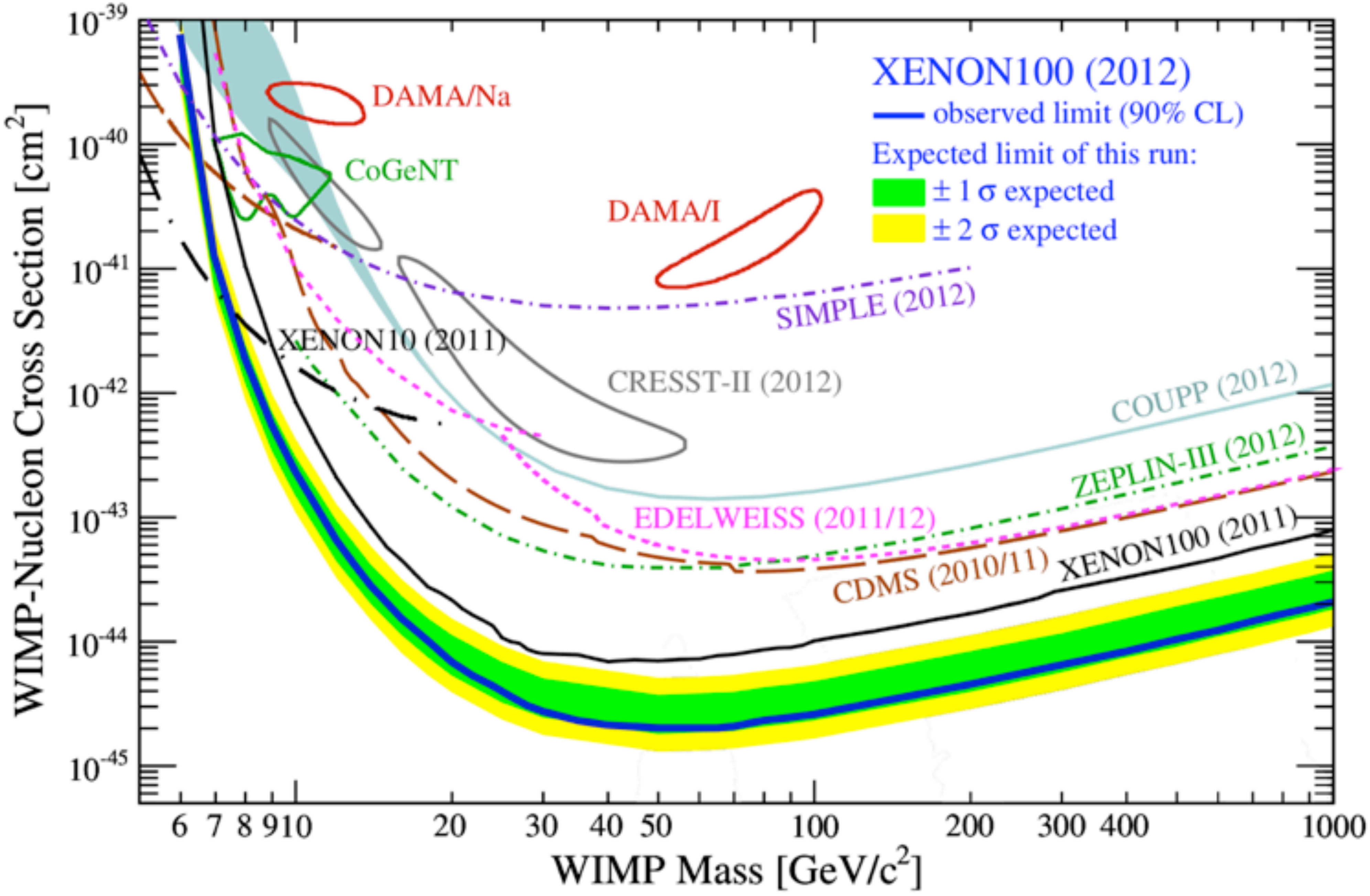
Constrain parameters by $\Omega_\chi < 1$

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 1.05 \times 10^{-5} h^2 \ \mathrm{GeVcm}^{-3}$$

PDG 14

Cosmology 3

- Experimental WIMP searches: direct detection



Mahmoudi et al. 2013

Cosmology 3

- **Dark energy**
- Evidence for dark energy
- Nature of dark energy?

Cosmology 3

- Evidence from observations of
- supernovae (→ Cosmology 1)
- large scale structure - BAO (baryon acoustic oscillations) in galaxy correlation functions
- CMB

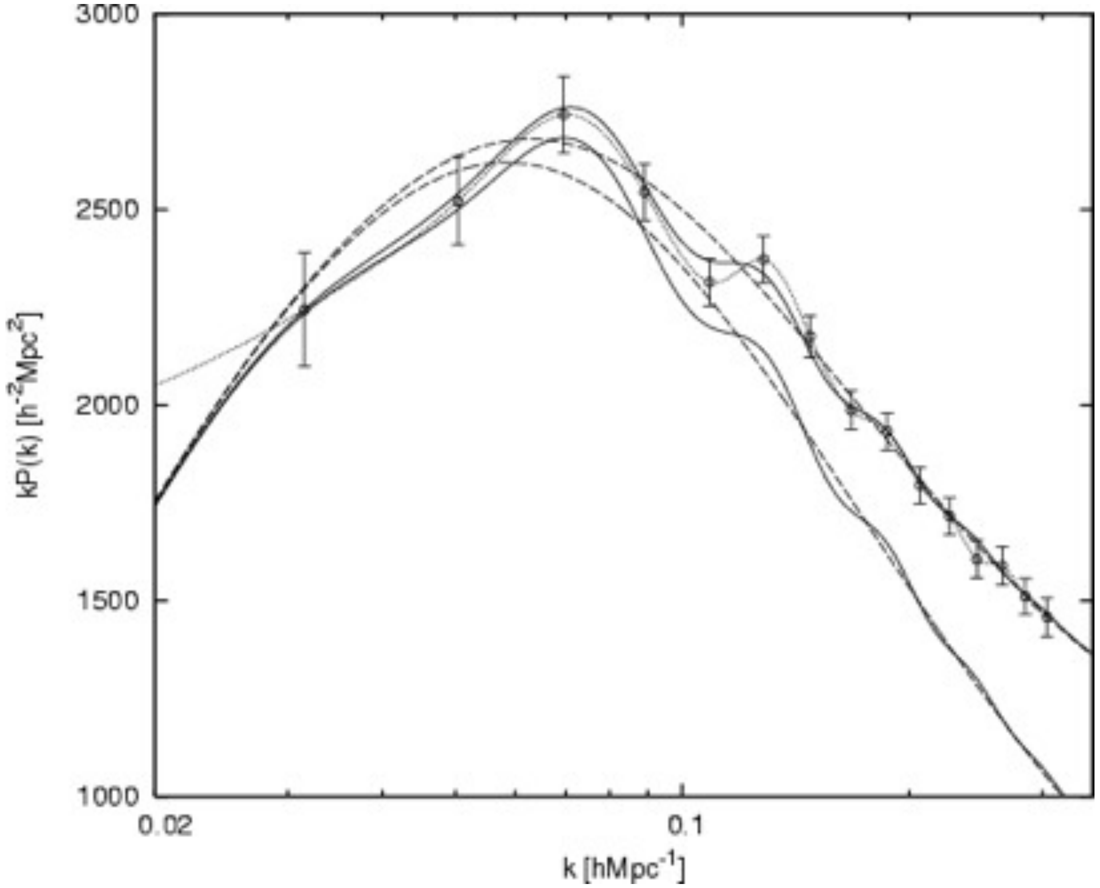
Cosmology 3

- **BAO - baryon acoustic oscillations and distance measurement**

- The acoustic oscillations of the baryon-fluid before decoupling lead to the acoustic peak structure observed in the angular power spectra of the CMB temperature anisotropies and polarization. They also manifest themselves in the clustering of galaxies at late times.

It has been detected

Huetsi 2005



SDSS LRG DR4

Cosmology 3

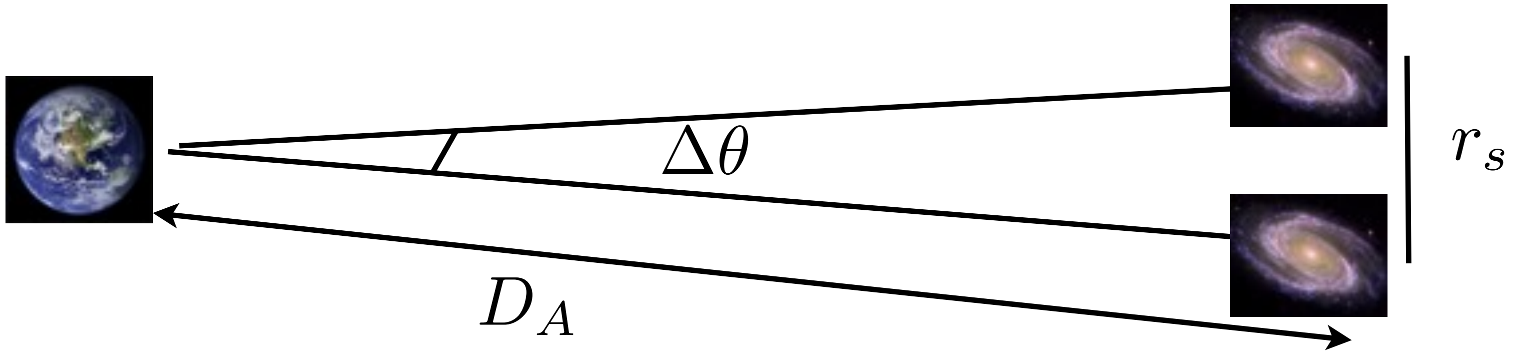
- **BAO - baryon acoustic oscillations and distance measureme**

$105h^{-1}\,\mathrm{Mpc}$ (comoving scale)

- Sound horizon at decoupling is characteristic scale of CMB fluctuations. It is imprinted in galaxy clustering today.

- In galaxy redshift survey measure at different redshifts:

- The preferred **angular separation** between galaxies at some redshift (perp. LOS).

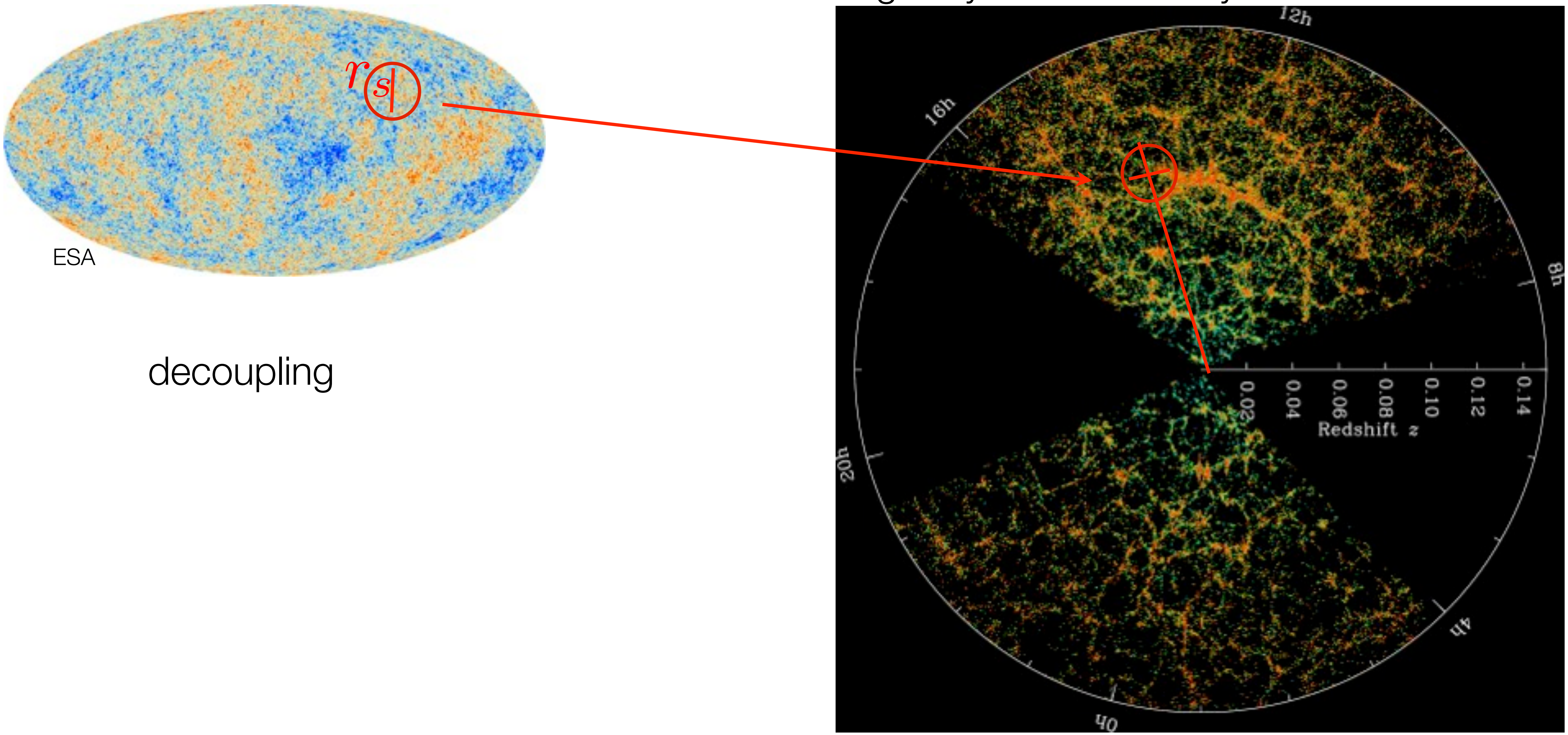


Along LOS:
redshift
separation

$$\Delta z = r_s H(z)/c$$

Cosmology 3

galaxy redshift survey



ESA

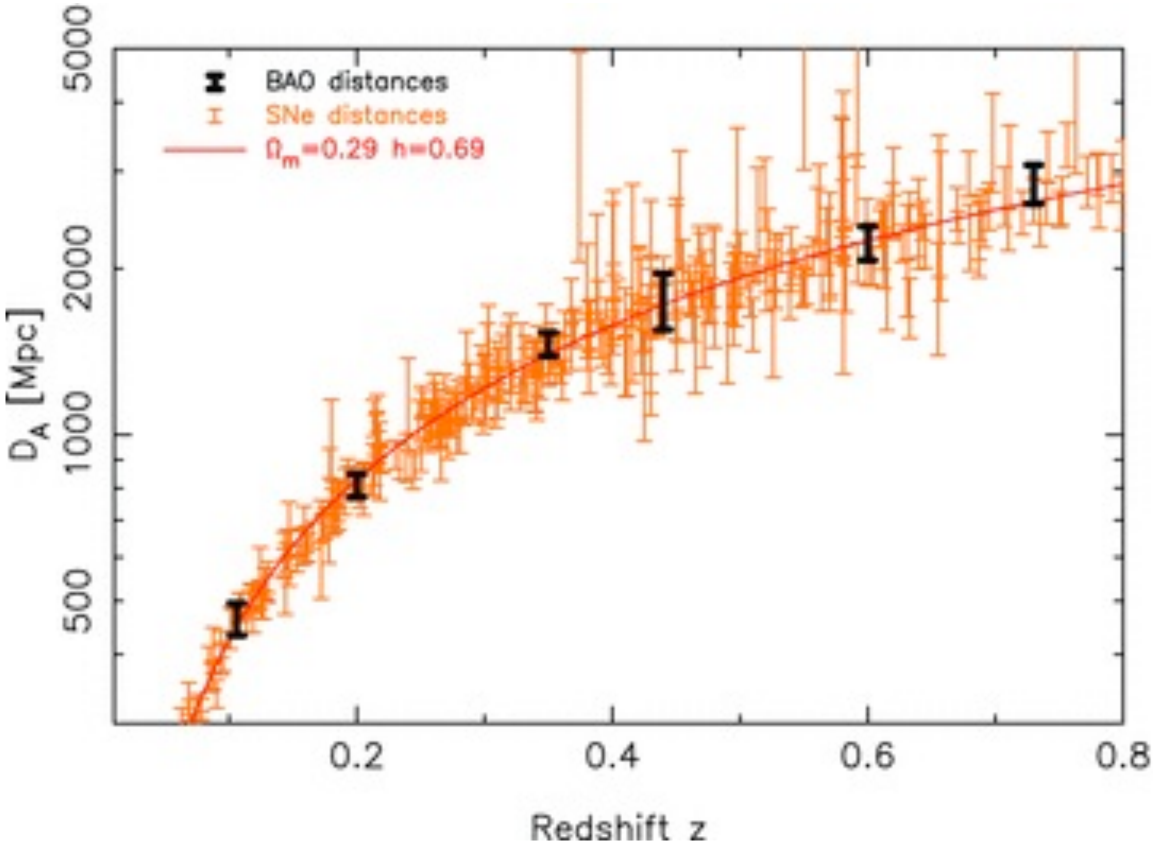
decoupling

~today

SDSS

Cosmology 3

WiggleZ: distance-redshift relation with BAO



Blake et al. 2011

Cosmology 3

- **CMB constraints on dark energy**

- A cosmological constant Λ can be effectively described as a perfect fluid with the equation of state

$$p_\Lambda = -\rho_\Lambda$$

$\Rightarrow$ ΛCDM

✓ leads to accelerated expansion

- There are other possible models using scalar fields or using a different theory of gravity (not Einstein general relativity).

- Allowing for a more general equation of state for dark energy with w a constant:

$$p_{DE} = w\rho_{DE}$$

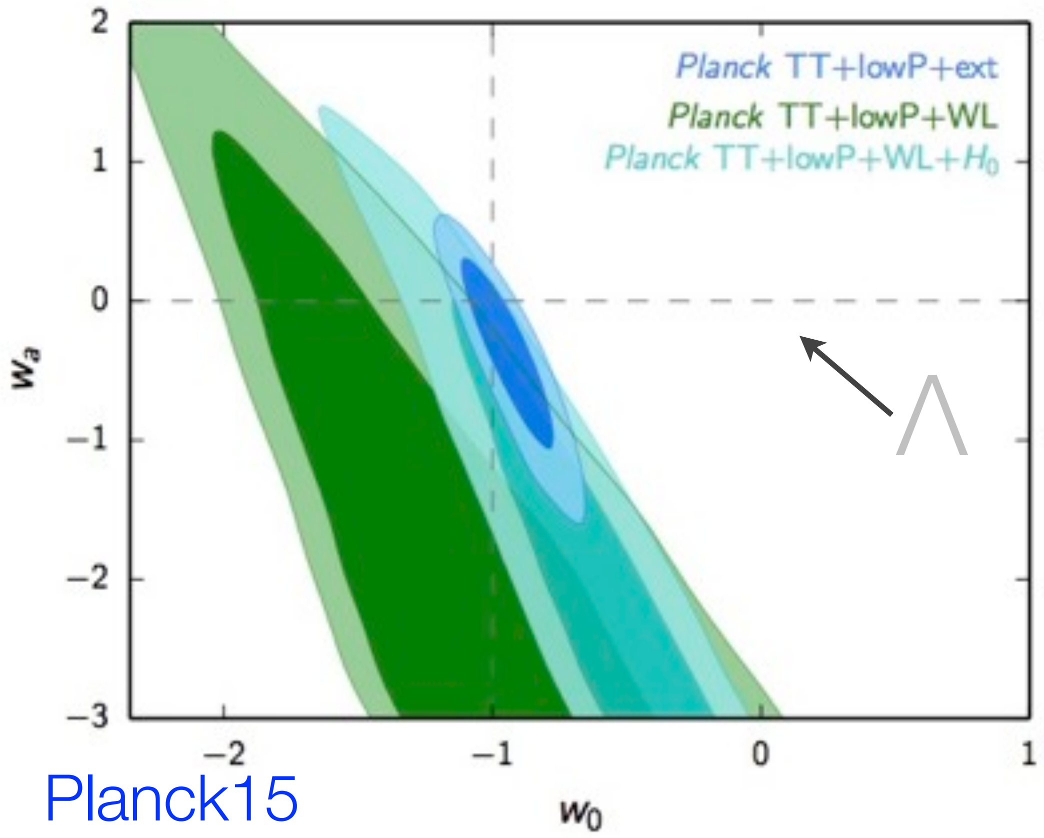
Cosmology 3

- Planck15 constraints on w: using Planck data + astrophysical data

$$\boxed{w = -1.006 \pm 0.045}$$

→ consistent with expected value for a cosmological constant

- Test more general, time-dependent equation of state:



Planck15

$$p_{DE} = w\rho_{DE}$$

with

scale factor

$$w = w_0 + (1-a)w_a$$

constants

Cosmology 3

- **Cosmological constant problem**

- Estimate the value of cosmological constant assuming that it is a vacuum energy density $\Lambda = 8\pi G\rho_{vac}$.

- Quantum field theory: describe vacuum fluctuations by simple harmonic oscillators → zero point energy $E = \frac{1}{2}\hbar\omega$

- To identify dark energy with vacuum fluctuations, integrate over all states in a volume V. Quantum states in volume V, with wave number $k = p/\hbar$ between k and k+dk and integrated over all directions, is $4\pi V k^2 dk/(2\pi)^3$.

Cosmology 3

- Total energy per unit volume of all oscillators:

$$\epsilon = \frac{E}{V} = \frac{\hbar}{4\pi^2}\int \omega_k k^2 dk \qquad \text{where} \qquad \omega_k^2 = k^2c^2 + \overset{\overset{\text{oscillator mass}}{\downarrow}}{m}{}^2 c^4/\hbar^2$$

- Integral divergent ⟶ introduce upper cut-off k_m or $E_m \gg mc^2$.

- Consider relativistic limit: $\omega_k \simeq kc$

$$\Rightarrow \quad \boxed{\epsilon = \frac{\hbar c}{16\pi^2} k_m^4 = \frac{E_m^4}{16\pi^2(\hbar c)^3}}$$

Cosmology 3

- What is the upper cut-off E_m ?

- Expect quantum field theory to fail at the Planck scale

⇒ $E_m = M_P$ ⇒ $\epsilon \sim 10^{121}\ \mathrm{GeV\,m^{-3}}$

- Observations give $\Omega_\Lambda \sim 0.7$ with $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$

$$\rho_c \simeq 5\,\mathrm{GeV\,m^{-3}}$$

$$\frac{\rho_\Lambda}{\epsilon} \simeq 10^{-121}$$

⇒ The observed value is only a tiny fraction of the predicted one.

Cosmology 3

- Conclusions
- Many open problems, e.g., what is dark matter? What is dark energy?
- Many observations and more will be coming in the near future.
- Astrophysical and cosmological observations can provide additional constraints on particle physics.